Carrier transport and recombination in *p*-doped and intrinsic 1.3 μm InAs/GaAs quantum-dot lasers

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The radiative and nonradiative components of the threshold current in 1.3 μm, *p*-doped and undoped quantum-dot semiconductor lasers were studied between 20 and 370 K. The complex behavior can be explained by simply assuming that the radiative recombination and nonradiative Auger recombination rates are strongly modified by thermal redistribution of carriers between the dots. The large differences between the devices arise due to the trapped holes in the *p*-doped devices. These both greatly increase Auger recombination involving hole excitation at low temperatures and decrease electron thermal escape due to their Coulombic attraction. The model explains the high T_0 values observed near room temperature.
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There has been considerable effort to produce 1.3-μm lasers with superior threshold characteristics based on the three-dimensional (3D) quantum confinement provided by semiconductor quantum dots (QDs).[1] Despite the fact that very high quality QD lasers with extremely low threshold current densities can be grown, they are still temperature sensitive.[2] Although a proposal to use *p* doping to improve the temperature characteristics of 1.3-μm QD lasers for telecommunications has been realized in practice,[3–5] the high values of the characteristic temperature, T_0, of the threshold current, I_{th}, ($T_0 = I_{th}(dI_{th}/dT)^{-1}$) has only been achieved over a narrow temperature range at the expense of a higher I_{th} compared to the intrinsic material.[3–5] The trend observed from the literature for QDs shows generally that a smaller threshold current density corresponds to a smaller value of the characteristic temperature.[2,6] It is also interesting to note that the nearly infinite T_0 in the *p*-doped lasers around room temperature (RT) reduces to ~60–70 K just above 60 °C.[4,5]

To understand the difference in the thermal characteristics of *p*-doped and intrinsic QD lasers we investigated the recombination mechanisms in both laser types by monitoring the unamplified spontaneous emission (SE) and lasing emission as a function of temperature between 20 and 370 K.[7] Unamplified SE was collected from a window milled in the substrate contact of the laser taking care to keep the collection efficiency constant during the experiment. Calculations show that the TM-polarized emission from the dots is small (less than 10%), therefore the value of the integrated SE, L, at the threshold current is proportional to the total radiative recombination rate; hence we were able to measure the temperature variation of the radiative part, I_{rad}, of the total threshold current. These direct measurements allow us to measure the relative contribution of the radiative and nonradiative components of I_{th} at different temperatures. It was shown in our previous study of undoped QD lasers that nonradiative Auger recombination is an important loss process in 1.3-μm QD lasers, and is responsible for the strong temperature sensitivity of these lasers around RT.[6,7] In this paper we show that all the complicated behavior of the devices may be explained in terms of the three basic processes: (i) radiative recombination, (ii) nonradiative Auger recombination, and (iii) thermalization of carriers between the dots.

The lasers investigated consist of 10 InAs QD stacks separated by modulation-doped or intrinsic GaAs barriers and sandwiched by GaAs separate-confinement layers and AlGaAs cladding layers.[4] Thus the transfer of holes from the acceptors to the QDs means that the dots in the *p*-doped devices are positively charged. The lasers were as cleaved with cavity lengths of 500 or 1000 μm. The lasers were studied both under cw and pulsed operation with a pulse duration of 500 ns and repetition rate of 10 kHz to avoid internal heating when the current densities were high.

The temperature behaviors of I_{th} and I_{rad} for both *p*-doped and intrinsic devices are given in Fig. 1. I_{th} and I_{rad} for the intrinsic device vary identically with temperature up to about $T=200$ K, demonstrating that nonradiative recombination is negligible in these devices at low temperature. This is also confirmed by the temperature dependence of L measured below I_{th} at a constant current $I=2$ mA given in Fig. 1. It shows that the radiative recombination efficiency is independent of temperature up to approximately 200 K. Therefore we normalized I_{rad} of the intrinsic device to I_{th} in this temperature range. However, I_{th} increases strongly above $T=200$ K with a characteristic temperature $T_0=50$ K in the temperature range $T=280$–360 K. At the same time, I_{rad} for the intrinsic device remains relatively constant up to $T=320$ K, indicating that the increase of I_{th} must be due to a nonradiative process, which was identified earlier as Auger recombination.[7] A small increase of I_{rad} above 320 K is caused by the effect of gain saturation,[6,8] which is less important in the *p*-doped lasers where the increase of I_{rad} occurs at a higher temperature of 340 K. Due to the higher peak gain in the *p*-doped devices, the lasing line of the 0.5-mm device switches from the ground state to the excited state at

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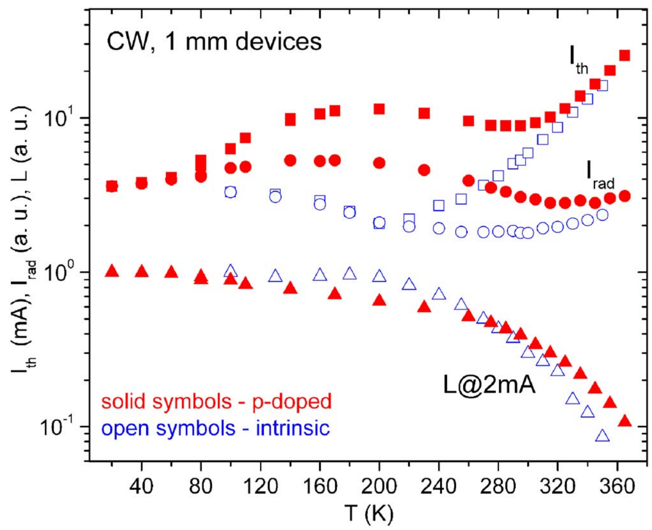

FIG. 1. (Color online) Temperature dependence of the threshold current, I_{th}, and its radiative component, I_{rad}, and integrated spontaneous emission, L, measured at a low current of $I=2$ mA in the 1-mm p-doped (solid symbols) and intrinsic (open symbols) devices.

higher temperature $T=340$ K compared to $T=320$ K for the intrinsic device.

In the p-doped device, I_{th} and I_{rad} follow one another only up to 60 K before the onset of a nonradiative process causes I_{th} to increase more quickly than I_{rad}. This is also illustrated by the decrease in L at a constant 2 mA above 60 K. Since I_{th} for the p-doped and undoped lasers is almost the same above 320 K, there is no reason to believe that there is any extra extrinsic nonradiative processes, such as defect recombination, present in the p-doped device. Therefore this effect is also likely to be due to Auger recombination that is enhanced at low temperatures due to the presence of a high density of holes compressed within the dots that would greatly increase processes involving hole excitation. This is the Auger process that has been observed to be the most important in 1.3-μm and 1.5-μm quantum well lasers around RT.[9]

The decrease in I_{th} and I_{rad} in the undoped device up to 200 K can be attributed to the thermal escape of carriers from the dots and transfer into the deeper levels (larger dots) where they can take part more effectively in the lasing process.[6,7] The high concentration of carriers that this involves may lead to enhanced Auger recombination, but in the undoped device its total magnitude remains negligible up to 200 K above which Auger recombination starts to dominate I_{th}. The improved thermalization results in a decrease in the full width at half maximum (FWHM) of the SE spectrum observed from the window.

In the p-doped dots, I_{rad} increases slightly between 60 and 180 K, which may be due to thermal broadening of the confined states and to the onset of thermal excitation of holes to higher confined states. I_{th}, which includes the additional Auger component, increases even more quickly and it is not until above 180 K that thermalization starts to decrease I_{th} and I_{rad}. The likely reason why thermalization does not start to become significant until higher temperatures in the p-doped devices than in the intrinsic devices is the increased confinement depth of electrons caused by the electrostatic attraction of the holes.

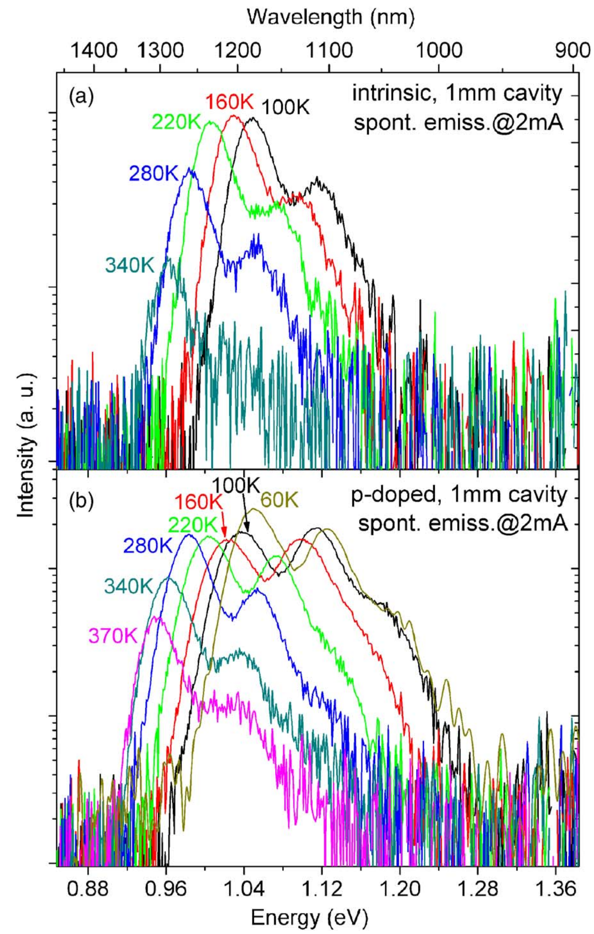

FIG. 2. (Color online) Spontaneous emission spectra of the (a) intrinsic and (b) p-doped lasers measured at $I=2$ mA at different temperatures.

I_{th} in the p-doped device is almost twice that in the undoped device at room temperature. However, from Fig. 1, we estimated that I_{rad} accounts for up to $\sim 30-40\%$ of I_{th} in both intrinsic and p-doped devices at $T=290$ K. These values are similar because not only the absolute values of I_{th}, but also the values of I_{rad} tend to converge at higher temperatures. Clearly the interplay between the temperature variation of the recombination processes and the temperature variation of carrier thermalization can be used to advantage, and in the p-doped devices can lead to an almost temperature-independent threshold current around room temperature.[4,5] The similar absolute value of I_{th} and the same temperature dependence of I_{th} above 330 K in both types of devices indicate that strong Auger recombination is the dominating recombination process in both laser types at high temperature.

To illustrate the variation of the spontaneous emission (SE) spectra with temperature, we plot in Fig. 2 the spectra for both types of devices measured at $I=2$ mA. The SE spectra of the intrinsic device contained emission from the ground state (GS) and the first excited state (ES) bands over the whole temperature range. Their peak positions and FWHM at $T=100$ K were 1.048 eV, 1.117 eV, and 45 meV, respectively. The SE spectrum of the p-doped device consisted of three bands whose energies at $T=100$ K were 1.037 eV, 1.114 eV, and about 1.185 eV for the GS, first ES, and second ES, respectively, with a FWHM(GS)=56 meV. This higher value of FWHM in the p-doped devices may be due to the variation in the number of holes trapped in the dots. This influences the transition energies within the dots and will add to the inhomogeneous broadening. We believe that the presence of the third band in the SE spectra at low temperatures arises due to the decreased thermalization of electrons compared to the intrinsic devices, as described above, and because the positively charged dots can more easily accommodate electrons.

At temperatures below $T=200$ K, the intensity of the ES band of the intrinsic device decreases with increasing T, while the intensity of the GS band increases slightly. These effects compensate each other so that the total integrated intensity of SE remains constant in this temperature interval (see Fig. 1). This shows that the effect of carrier redistribution between the dots increases the population of lower energy states with increasing T and leads to the decrease of the threshold current with increasing temperature up to $T=200$ K. Above this temperature the intensity of both GS and ES bands decreased with increasing temperature at nearly the same rate, demonstrating the decrease of the radiative recombination efficiency due to Auger recombination. This correlates with the strong increase of I_{th} shown in Fig. 1.

The presence of Auger recombination in the p-doped devices at low temperature along with the thermal improvement of carrier thermalization makes the thermal behavior of SE in these devices very unusual and much more complicated. Below $T=60$ K the shapes of the SE spectra do not change but at temperatures $T=60-100$ K, the intensity of the GS emission in the p-doped QDs decreases more strongly with increasing T than the emission intensity of the excited states, which may be caused by increasing Auger recombination and some lack of carrier thermalization to the GS. In the temperature interval $T=100-160$ K the trend reversed and the emission intensity of the excited states begins to decrease much faster with increasing T than the intensity of the GS band due to the onset of carrier redistribution between the dots (the second ES band nearly vanishes from the spectrum at $T=160$ K). In the temperature range of $T=160-280$ K, where the influence of the improved carrier redistribution and thermalization is larger, the intensity of the ES band continues to decrease with increasing T, while the intensity of the GS band increases slightly. Finally, at temperatures above $T=280$ K, where carriers are close to thermal equilibrium, both GS and ES emission intensities start to decrease with increasing T with the same rate due to increased Auger recombination as it was observed in the intrinsic devices above 200 K.

In addition, the pinning of the integrated SE intensity, L, above the lasing threshold (to be discussed elsewhere) improves with increasing temperature in both devices. Both L and the GS peak intensity pin almost ideally in the intrinsic device at higher temperatures ($T=300-350$ K). However, in the p-doped device L does not pin even at higher temperature, while the GS peak intensity pins well above RT demonstrating some lack of carrier thermalization within the p-doped QD system due to the increased potential barriers for electrons in the doped devices.

In conclusion, we found that I_{th} in the intrinsic devices is dominated by radiative recombination up to 200 K and decreases with increasing temperature due to the improved thermalization of carriers between the dots. This effect is less above 200 K, as indicated by the nearly constant value of I_{rad}, but the onset of nonradiative Auger recombination causes I_{th} to start to increase strongly with increasing temperature. In the p-doped QD lasers nonradiative recombination is present even at low temperature, due to the relatively large number of holes in the dots. This increases I_{th} compared to the intrinsic devices and causes it to increase further with increasing temperature up to 180 K. Thermalization of electrons between the p-doped dots does not cause I_{th} to decrease until above 180 K, because the electrostatic attraction of the holes increases the effective barrier for electron escape. Above 330 K the temperature dependencies and absolute values of I_{th} in the undoped and p-doped devices are almost identical. This can be explained if Auger recombination is dominant in both. This complicated interplay of carrier thermalization with the radiative and nonradiative recombination processes is supported by analysis of the spontaneous emission spectra in the doped and undoped samples. Interestingly, introducing the correct degree of p doping can cause the opposing effects of carrier thermalization and Auger recombination to cancel around room temperature, leading to an almost temperature-independent I_{th}, or infinite T_0.

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